

# The Formation of Massive Stars

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Massive stars have a profound influence on the Universe, but their formation remains poorly understood. We review the current status of observational and theoretical research in this field, describing the various stages of an evolutionary sequence that begins with cold, massive gas cores and ends with the dispersal and ionization of gas by the newly-formed star. The physical processes in massive star formation are described and related to their observational manifestations. Feedback processes and the relation of massive stars to star cluster formation are also discussed. We identify key observational and theoretical questions that future studies should address.

## 1. Introduction

Massive star formation has drawn considerable interest for several decades, but the last 10 years have witnessed a strong acceleration of theoretical and observational research in this field. One of the major conceptual problems in massive star formation arises from the radiation pressure massive stars exert on the surrounding dust and gas core (e.g., *Kahn, 1974; Wolfire and Cassinelli, 1987; Jijina and Adams, 1996; Yorke and Sonnhalter, 2002; Krumholz et al., 2005b*). In principle, this radiation pressure could be strong enough to stop further accretion, which would imply that the standard theory of low-mass star formation had to be adapted to account for the formation of massive stars. Two primary approaches have been followed to overcome these problems: the first and more straightforward approach is to modify the standard theory quantitatively rather than qualitatively. Theories have been proposed that invoke varying dust properties (e.g., *Wolfire and Cassinelli, 1987*), increasing accretion rates in turbulent cloud cores of the order  $10^{-4} - 10^{-3} M_{\odot} \text{ yr}^{-1}$  compared to  $\sim 10^{-6} M_{\odot} \text{ yr}^{-1}$  for low-mass star formation (e.g., *Norberg and Maeder, 2000; McKee and Tan, 2003*), accretion via disks (e.g., *Jijina and Adams, 1996; Yorke and Sonnhalter, 2002*), accretion through the evolving hypercompact HII region (*Keto, 2003; Keto and Wood, 2006*), the escape of radiation through wind-blown cavities (*Krumholz et al., 2005a*) or radiatively driven Rayleigh-Taylor instabilities (*Krumholz et al., 2005b*). These variations to the

standard picture of low-mass star formation suggest that massive stars can form within an accretion-based picture of star formation. Contrary to this, a paradigm change for the formation of massive stars has been proposed based on the observational fact that massive stars always form at the dense centers of stellar clusters: the coalescence scenario. In this scenario, the protostellar and stellar densities of a forming massive cluster are high enough ( $\sim 10^8 \text{ pc}^{-3}$ ) that protostars undergo physical collisions and merge, thereby avoiding the effects of radiation pressure (*Bonnell et al., 1998; Bally and Zinnecker, 2005*). Variants of the coalescence model that operate at lower stellar densities have been proposed by *Stahler et al. (2000)* and by *Bonnell and Bate (2005)*. A less dramatic approach suggests that the bulk of the stellar mass is accreted via competitive accretion in a clustered environment (*Bonnell et al., 2004*). This does not necessarily require the coalescence of protostars, but the mass accretion rates of the massive cluster members would be directly linked to the number of their stellar companions, implying a causal relationship between the cluster formation process and the formation of higher-mass stars therein.

We propose an evolutionary scenario for massive star formation, and then discuss the various stages in more detail. Following *Williams et al. (2000)*, we use the term *clumps* for condensations associated with cluster formation, and the term *cores* for molecular condensations that form single or gravitationally bound multiple massive protostars. The evolutionary sequence we propose for high-mass star-forming cores is:

High-Mass Starless Cores (HMSCs)

- High-Mass Cores harboring accreting Low/Intermediate-Mass Protostar(s) destined to become a high-mass star(s)
- High-Mass Protostellar Objects (HMPOs)
- Final Stars.

The term HMPO is used here in a literal sense, i.e., accreting high-mass protostars. Hence, the HMPO group consists of protostars  $>8 M_{\odot}$ , which early on have not necessarily formed a detectable Hot Molecular Core (HMC) and/or Hypercompact HII region (HCHII, size  $< 0.01$  pc). HMCs and HCHII might coexist simultaneously. Ultracompact HII regions (UCHII, size  $< 0.1$  pc) are a transition group: some of them may still harbor accreting protostars (hence are at the end of the HMPO stage), but many have likely already ceased accretion (hence are part of the Final-Star class). High-mass stars can be on the main sequence while they are deeply embedded and actively accreting as well as after they cease accreting and become Final Stars. The class of High-Mass Cores harboring accreting Low/Intermediate-Mass Protostars has not been well studied yet, but there has to be a stage between the HMSCs and the HMPOs, consisting of high-mass cores with embedded low/intermediate-mass objects. On the cluster/clump scale the proposed evolutionary sequence is:

Massive Starless Clumps

- Protoclusters
- Stellar Clusters.

By definition, Massive Starless Clumps can harbor only HMSCs (and low-mass starless cores), whereas Protoclusters in principle can harbor all sorts of smaller-scale entities (low- and intermediate-mass protostars, HMPOs, HMCs, HCHII, UCHII and even HMSCs).

This review discusses the evolutionary stages and their associated physical processes (§2, 3, 4, 6), feedback processes (§4), and cluster formation (§5), always from an observational *and* theoretical perspective. We restrict ourselves to present day massive star formation in a typical Galactic environment. Primordial star formation, lower metallicities or different dust properties may change this picture (e.g., *Bromm and Loeb*, 2004; *Draine*, 2003). The direct comparison of the theoretical predictions with the observational evidences and indications shows the potentials and limitations of our current understanding of high-mass star formation. We also refer to the IAU227 Proceedings dedicated to Massive Star Birth (*Cesaroni et al.*, 2005b).

## 2. Initial conditions of massive star/cluster formation

### 2.1. Observational results

The largest structures within our Galaxy are Giant Molecular Clouds (GMCs) with sizes from  $\sim 20$  to  $\sim 100$  pc and masses between  $\sim 10^4$  to  $\sim 10^6 M_{\odot}$ . The physical properties have been discussed in many reviews (e.g., *McKee*, 1999; *Evans*, 1999), and we summarize only the most important characteristics. A multi-transition survey of GMCs in our Galaxy shows that the average local density derived from an LVG analysis is  $\rho_H \sim 4 \times 10^3 - 1.2 \times 10^4 \text{ cm}^{-3}$

and the temperature is  $\sim 10 - 15$  K (e.g., *Sanders et al.*, 1993), giving a typical Bonnor-Ebert mass  $\sim 2 M_{\odot}$ . The volume-averaged densities in GMCs are  $\rho_H \sim 50$  to  $100 \text{ cm}^{-3}$ ; these are substantially less than the local density values, indicating that the molecular gas is highly clumped. Velocity dispersions of  $2-3 \text{ km s}^{-1}$  indicate highly supersonic internal motions given that the typical sound speed is  $\sim 0.2 \text{ km s}^{-1}$ . These motions are largely due to turbulence (e.g., *MacLow and Klessen*, 2004; *Elmegreen and Scalo*, 2004). Measured magnetic field strengths are of the order a few  $10 \mu\text{G}$  (e.g., *Crutcher*, 1999; *Bourke et al.*, 2001). Depending on the size-scales and average densities, magnetic critical masses can range from  $\sim 5 \times 10^5 M_{\odot}$  to a few solar masses, corresponding to GMCs and low-mass star-forming regions, respectively (*McKee*, 1999). Thus, although the rather low Jeans masses indicate gravitationally bound and likely unstable entities within GMCs, turbulence and magnetic stresses appear to be strong enough to support the GMCs against complete collapse on large scales.

Most important for any star formation activity, GMCs show sub-structures on all spatial scales. They contain dense gas clumps that are easily identifiable in the (sub)mm continuum and high-density molecular line tracers (e.g., *Plume et al.*, 1992; *Bronfman et al.*, 1996; *Beuther et al.*, 2002a; *Mueller et al.*, 2002; *Faundez et al.*, 2004; *Beltrán et al.*, 2006). Peak densities in such dense clumps can easily reach  $10^6 \text{ cm}^{-3}$ , and the massive dense clumps we are interested in typically have masses between a few 100 and a few  $1000 M_{\odot}$  (e.g., *Beuther et al.*, 2002a; *Williams et al.*, 2004; *Faundez et al.*, 2004). Massive dense clumps are the main locations where high-mass star formation is taking place. We shall concentrate on the physical properties and evolutionary stages of clumps of dense molecular gas and dust.

Most observational high-mass star formation research in the last decade has focused on HMPOs and UCHII regions. These objects have mid-infrared emission from hot dust and thus already contain an embedded massive protostellar source. Earlier evolutionary stages at the onset of massive star formation were observationally largely inaccessible because no telescope existed to identify these objects. The most basic observational characteristics of the earliest stages of massive star formation, prior to the formation of any embedded heating source, should be that they are strong cold dust and gas emitters at (sub)mm wavelengths, and weak or non-detections in the mid-infrared because they have not yet heated a warm dust cocoon. The advent of the mid-infrared Space Observatories ISO and MSX permitted for the first time identifications of large samples of potential (Massive) Starless Clumps, the Infrared Dark Clouds (IRDCs, e.g., *Egan et al.*, 1998; *Bacmann et al.*, 2000; *Carey et al.*, 2000). Fig. 1 shows a series of IRDCs as seen with SPITZER/GLIMPSE. Various groups work currently on massive IRDCs, but so far not much has been published. Some initial ideas about observational quantities at the initial stages of massive cloud collapse were discussed by *Evans et al.* (2002). *Garay et al.* (2004) presented early mm observations of a sample of 4 sources, other re-

cent statistical identifications and studies of potential HMSCs or regions at the onset of massive star formation can be found in *Hill et al. (2005)*, *Klein et al. (2005)*, *Sridharan et al. (2005)*, and *Beltrán et al. (2006)*.

These massive dense clumps have masses between a few 100 and a few 1000  $M_{\odot}$ , sizes of the order 0.25-0.5 pc, mean densities of  $10^5 \text{ cm}^{-3}$ , and temperatures of order 16 K. While the masses and densities are typical for high-mass star-forming regions, the temperatures derived, for example, from  $\text{NH}_3$  observations (around 16 K, *Sridharan et al., 2005*) are lower than those toward young HMPOs and UCHII regions (usually  $\geq 22$  K, e.g., *Churchwell et al., 1990*; *Sridharan et al., 2002*). Furthermore, the measured  $\text{NH}_3$  line-widths from the IRDCs are narrow as well; *Sridharan et al. (2005)* found mean values of  $1.6 \text{ km s}^{-1}$  whereas HMPOs and UCHIIs have mean values of 2.1 and  $3.0 \text{ km s}^{-1}$ , respectively (*Churchwell et al., 1990*; *Sridharan et al., 2002*). The narrow line-widths and low temperatures support the idea that IRDCs represent an earlier evolutionary stage than HMPOs and UCHII regions, with less internal turbulence. Although subject to large uncertainties, a comparison of the virial masses calculated from  $\text{NH}_3$  data with the gas masses estimated from 1.2 mm continuum emission indicates that most candidate HMSCs are virially bound and prone to potential collapse and star formation (*Sridharan et al., 2005*).

The IRDCs are not a well defined class, but are expected to harbor various evolutionary stages, from genuine HMSCs via High-Mass Cores harboring accreting Low/Intermediate-Mass Protostars to the youngest HMPOs. While the first stage provides good targets to study the initial conditions of massive star formation prior to cloud collapse, the other stages are important to understand the early evolution of massive star-forming clumps. For example, the source HMSC18223-3 is probably in such an early accretion stage: Correlating high-spatial-resolution mm observations from the Plateau de Bure Interferometer with SPITZER mid-infrared observations, *Beuther et al. (2005c)* studied a massive dust and gas core with no protostellar mid-infrared counterpart in the GLIMPSE data. While this could also indicate a genuine HMSC, they found relatively high temperatures ( $\sim 33$  K from  $\text{NH}_3(1,1)$  and  $(2,2)$ ), an increasing  $\text{N}_2\text{H}^+(1-0)$  line-width from the core edge to the core center, and so called "green fuzzy" mid-infrared emission at the edge of the core in the IRAC data at  $4.5 \mu\text{m}$ , indicative of molecular outflow emission. The outflow scenario is supported by strong non-Gaussian line-wing emission in  $\text{CO}(2-1)$  and  $\text{CS}(2-1)$ . These observational features are interpreted as circumstantial evidence for early star formation activity at the onset of massive star formation. Similar results toward selected IRDCs have recently been reported by, e.g., *Rathborne et al. (2005)*, *Ormel et al. (2005)*, *Birkmann et al. (2006)* and *Pillai et al. (2006)*. Interestingly, none of these IRDC case studies has revealed a true HMSC yet. However, with the given low number of such studies, we cannot infer whether this is solely a selection effect or whether HMSCs are genuinely rare.

Recent large-scale mm-continuum mapping of Cygnus-X revealed approximately the same number of infrared-quiet sources compared with infrared-bright HMPO-like regions (*Motte et al., 2005*). However, none of these infrared-quiet sources appears to be a genuine HMSC, and hence they could be part of the class of High-Mass Cores harboring accreting Low/Intermediate-Mass Protostars. A few studies report global infall on large spatial scales (e.g., *Rudolph et al., 1990*; *Williams and Garland, 2002*; *Peretto et al., 2006*; *Motte et al., 2005*), suggesting that massive clumps could form from lower-density regions collapsing during the early star formation process.

The earliest stages of massive star formation, specifically massive IRDCs, have received increased attention over the past few years, but some properties like the magnetic field have so far not been studied at all. Since this class of objects is observationally rather new, we are expecting many exciting results in the coming years.

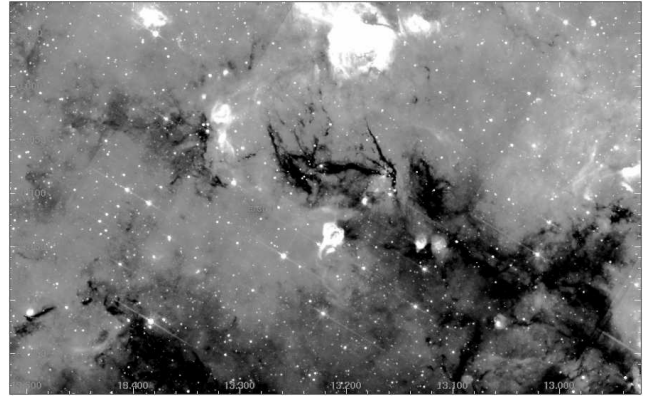


Fig. 1.— Example image of IRDCs observed against the Galactic background with the SPITZER GLIMPSE survey in the  $8 \mu\text{m}$  band (*Benjamin et al., 2003*).

## 2.2. Theory

A central fact about GMCs is that they are turbulent (*Larson, 1981*). The level of turbulence can be characterized by the virial parameter  $\alpha_{\text{vir}} \equiv 5\sigma^2 R/GM$ , where  $\sigma$  is the rms 1D velocity dispersion,  $R$  the mean cloud radius, and  $M$  the cloud mass;  $\alpha_{\text{vir}}$  is proportional to the ratio of kinetic to gravitational energy (*Myers and Goodman, 1988*; *Bertoldi and McKee, 1992*). The large-scale surveys of GMCs by *Dame et al. (1986)* and *Solomon et al. (1987)* give  $\alpha_{\text{vir}} \simeq 1.3 - 1.4$  (*McKee and Tan, 2003*), whereas regions of active low-mass star formation have  $\alpha_{\text{vir}} \simeq 0.9$  (e.g., *Onishi et al., 1996*). For regions of massive star formation, *Yonekura et al. (2005)* find  $0.5 \lesssim \alpha_{\text{vir}} \lesssim 1.4$ .

The great advance in our understanding of the dynamics of GMCs in the past decade has come from simulations of the turbulence in GMCs (e.g., *Elmegreen and Scalo, 2004*; *Scalo and Elmegreen, 2004*; *MacLow and Klessen, 2004*). One of the primary results of these studies is that turbulence

decays in less than a crossing time. A corollary of this result is that it is difficult to transmit turbulent motions for more than a wavelength. These results raise a major question: since most of the sources of interstellar turbulence are intermittent in both space and time, how is it possible to maintain the high observed levels of turbulence in the face of such strong damping? Simulations without driven turbulence, such as those used to establish the theory of competitive accretion (e.g., *Bonnell et al.*, 2001a; see §3.2), reach virial parameters  $\alpha_{\text{vir}} \ll 1$ , far less than observed.

The results of these turbulence simulations have led to two competing approaches to the modeling of GMCs and the gravitationally bound structures (clumps) within them: as quasi-equilibrium structures or as transient objects. The first approach builds on the classical analysis of *Spitzer*, (1978) and utilizes the steady-state virial theorem (*Chieze*, 1987; *Elmegreen*, 1989; *Bertoldi and McKee*, 1992; *McKee*, 1999). This model naturally explains why GMCs and the bound clumps within them have virial parameters of order unity (provided the magnetic field has a strength comparable to that observed) and why their mean column densities in the Galaxy are  $\sim 10^{22} \text{ H cm}^{-2}$ . In order to account for the ubiquity of the turbulence, such models must assume that: (1) the turbulence actually decays more slowly than in the simulations, perhaps due to an imbalanced MHD cascade (*Cho and Lazarian*, 2003); (2) the energy cascades into the GMC or clump from larger scales; and/or (3) energy injection from star formation maintains the observed level of turbulence (*Norman and Silk*, 1980; *McKee*, 1989; *Matzner*, 2002). Recent simulations by *Li and Nakamura* (in prep.) are consistent with the suggestion that protostellar energy injection can indeed lead to virial motions in star-forming clumps (see §4.2). In the alternative view, the clouds are transient and the observed turbulence is associated with their formation (*Ballesteros-Paredes et al.*, 1999; *Elmegreen*, 2000; *Hartmann et al.*, 2001; *Clark et al.*, 2005; *Heitsch et al.*, 2005). *Bonnell et al.* (2006) propose that the observed velocity dispersion in molecular clouds could be due to clumpy molecular gas passing through galactic spiral shocks. While these theories naturally account for the observed turbulence, they do not explain why GMCs have virial parameters of order unity, nor do they explain why clouds that by chance live longer than average do not have very low levels of turbulence. Quasi-equilibrium models predict that star formation will occur over a longer period of time than do transient cloud models. How these predictions compare with observations of high-mass star formation regions will be discussed in §5.2 below.

### 3. High-Mass Protostellar Objects

#### 3.1. Observational results

General properties: The most studied objects in massive star formation research are HMPOs and UCHII regions. This is partly because the IRAS all sky survey permitted detection and identification of a large number of such sources from which statistical studies could be un-

dertaken (e.g., *Wood and Churchwell*, 1989a; *Plume et al.*, 1992; *Kurtz et al.*, 1994; *Shepherd and Churchwell*, 1996; *Molinari et al.*, 1996; *Sridharan et al.*, 2002; *Beltrán et al.*, 2006). The main observational difference between young HMPOs/HMCs and UCHII regions is that the former are weak or non-detections in the cm-regime due to undetectable free-free emission (for a UCHII discussion see, e.g., *Churchwell*, 2002, and the chapter by *Hoare et al.*). Although in our classification typical HMCs with their high temperatures and complex chemistry are a subset of HMPOs, we expect that every young HMPO must already have heated a small central gas core to high temperatures, and it is likely that sensitive high-spatial resolution observations will reveal small HMC-type structures toward all HMPOs. This is reminiscent of the so-called Hot Corinos found recently in some low-mass star-forming cores (see the chapter by *Ceccarelli et al.*).

Many surveys have been conducted in the last decade characterizing the physical properties of massive star-forming regions containing HMPOs (e.g., *Plume et al.*, 1997; *Molinari et al.*, 1998; *Sridharan et al.*, 2002; *Beuther et al.*, 2002a; *Mueller et al.*, 2002; *Shirley et al.*, 2003; *Walsh et al.*, 2003; *Williams et al.*, 2004; *Faundez et al.*, 2004; *Zhang et al.*, 2005; *Hill et al.*, 2005; *Klein et al.*, 2005; *Beltrán et al.*, 2006). While the masses and sizes are of the same order as for the IRDCs (a few 100 to a few 1000  $M_{\odot}$  and of the order 0.25-0.5 pc, §2), mean densities can exceed  $10^6 \text{ cm}^{-3}$ , and mean surface densities, although with a considerable spread, are reported around  $1 \text{ g cm}^{-2}$  (for a compilation see *McKee and Tan*, 2003). In contrast to earlier claims that the density distributions  $\rho \propto r^{-k_{\rho}}$  of massive star-forming clumps may have power-law indices  $k_{\rho}$  around 1.0, several studies derived density distributions with mean power-law indices  $k_{\rho}$  around 1.5 (*Beuther et al.*, 2002a; *Mueller et al.*, 2002; *Hatchell and van der Tak*, 2003; *Williams et al.*, 2004), consistent with density distributions observed toward regions of low-mass star formation (e.g., *Motte and André*, 2001). However, one has to bear in mind that these high-mass studies analyzed the density distributions of the gas on cluster-scales whereas the low-mass investigations trace scales of individual or multiple protostars. Mean temperatures ( $\sim 22 \text{ K}$ , derived from  $\text{NH}_3$  observations) and  $\text{NH}_3(1,1)$  line widths ( $\sim 2.1 \text{ km s}^{-1}$ ) are also larger for HMPOs than for IRDCs.

Furthermore, HMPOs are often associated with  $\text{H}_2\text{O}$  and Class II  $\text{CH}_3\text{OH}$  maser emission (e.g., *Walsh et al.*, 1998; *Kylafis and Pavlakis*, 1999; *Beuther et al.*, 2002c; *Codella et al.*, 2004; *Pestalozzi et al.*, 2005; *Ellingsen*, 2006). While the community agrees that both maser types are useful signposts of massive star formation ( $\text{H}_2\text{O}$  masers are also found in low-mass outflows), there is no general agreement what these phenomena actually trace in massive star-forming regions. Observations indicate that both species are found either in molecular outflows (e.g., *De Buizer*, 2003; *Codella et al.*, 2004) or in potential massive accretion disks (e.g., *Norris et al.*, 1998; *Torrelles et al.*, 1998). In a few cases, such as very high spatial resolution VLBI studies, it has

been possible to distinguish between an origin in a disk and an outflow (e.g., *Torrelles et al.*, 2003; *Pestalozzi et al.*, 2004; *Goddi et al.*, 2005), but, in general, it is mostly not possible to distinguish between the two possibilities.

One of the most studied properties of HMPOs are the massive molecular outflows found to be associated essentially with all stages of early massive star formation. For a discussion of this phenomenon and its implications see §4.

**Massive disks:** Disks are an essential property of the accretion-based formation of high-mass stars. The chapter by *Cesaroni et al.* provides a detailed discussion about observations and modeling of disks around massive protostellar objects. We simply summarize that massive, Keplerian disks have been observed around early-B-type stars, the best known example being IRAS 20126+4102 (*Cesaroni et al.*, 1997, 1999, 2005a; *Zhang et al.*, 1998). Venturing further to higher-mass sources, several studies found rotating structures perpendicular to molecular outflows, indicative of an inner accretion disk (e.g., *Zhang et al.*, 2002; *Sandell et al.*, 2003; *Beltrán et al.*, 2004; *Beuther et al.*, 2005b). However, these structures are not necessarily Keplerian and could be larger-scale toroids, rotating around the central forming O-B cluster as suggested by *Cesaroni* (2005). Recently *van der Tak and Menten* (2005) conclude from 43 GHz continuum observations that massive star formation at least up to  $10^5 L_{\odot}$  proceeds through accretion with associated collimated molecular outflows. A detailed theoretical and observational understanding of massive accretion disks is one of the important issues for future high-mass star formation studies.

**SEDs:** Spectral energy distributions (SEDs) have often been used to classify low-mass star-forming regions and to infer their physical properties (e.g., *Lada and Wilking*, 1984; *André et al.*, 1993). In massive star formation, deriving SEDs for individual high-mass protostellar sources proves to be more complicated. Problems arise because of varying spatial resolution with frequency, varying telescope sensitivity, and disk orientation to the line of sight. While we can resolve massive cluster-forming regions in the (sub)mm regime (e.g., *Cesaroni et al.*, 1999; *Shepherd et al.*, 2003; *Beuther and Schilke*, 2004) and at cm wavelengths (e.g., *Wood and Churchwell*, 1989b; *Kurtz et al.*, 1994; *Gaume et al.*, 1995; *De Pree et al.*, 2000), near-/mid and far-infrared wavelength data for individual sub-sources are difficult to obtain. The earliest evolutionary stages are generally so deeply embedded that they are undetectable at near-infrared wavelengths, and until recently this was also a severe problem at mid-infrared wavelength (although a few notable exceptions exist, e.g., *De Buizer et al.*, 2002; *Linz et al.*, 2005). The advent of the SPITZER Space Telescope now allows deep imaging of such regions and will likely reveal many objects. However, even with SPITZER the spatial resolution in the far-infrared regime, where the SEDs at early evolutionary stages peak, is usually not good enough ( $16''$  pixels) to spatially resolve the massive star-forming clusters. The only statistically relevant data at far-infrared wavelengths so far stem from the IRAS satellite,

which had a spatial resolution of approximately  $100''$ . Although the IRAS data have proven very useful in identifying regions of massive star formation (e.g., *Wood and Churchwell*, 1989a; *Molinari et al.*, 1996; *Sridharan et al.*, 2002; *Beltrán et al.*, 2006), they just give the fluxes integrated over the whole star-forming cluster and thus hardly constrain the emission of individual cluster members. Nevertheless, the IRAS data were regularly employed to estimate the integrated luminosity of young massive star-forming regions by two-component grey-body fits (e.g., *Hunter et al.*, 2000; *Sridharan et al.*, 2002), and to set additional constraints on the density distributions of the regions (e.g., *Hatchell and van der Tak*, 2003). SED modeling allows one to infer the characteristics of protostars in massive star-forming regions (*Osorio et al.*, 1999). *Chakrabarti and McKee* (2005) showed that the far-IR SEDs of protostars embedded in homogeneous, spherical envelopes are characterized by the density profile in the envelope and by two dimensionless parameters, the light-to-mass ratio,  $L/M$ , and the surface density of the envelope,  $\Sigma = M/(\pi R^2)$ . If these parameters are determined from the SED and if one knows the distance, then it is possible to infer both the mass and accretion rate of the protostar (*McKee and Chakrabarti*, 2005). *Whitney et al.* (2005) and *De Buizer et al.* (2005) have determined the effects of disks on the SEDs. Recent 3-D modeling by *Indebetouw et al.* (2006) shows how sensitive the SEDs, especially below  $100 \mu\text{m}$ , are to the clumpy structure of the regions and to the observed line of sights. For example, they are able to fit the entire sample of UCHII regions studied by *Faison et al.* (1998) with the same clumpy model because the varying line of sights produce very different SEDs. Hence, SEDs alone do not provide sufficient information to infer the properties of clumpy sources, and it will be essential to obtain additional information by mapping these sources with powerful observatories such as the SMA, CARMA in 2006, ALMA at the end of the decade and JWST in the next decade.

**Chemistry:** Young massive star-forming regions, and specifically HMCs, exhibit a rich chemistry from simple two-atom molecules to large organic carbon chains (e.g., *Blake et al.*, 1987; *Schilke et al.*, 1997, 2001). While these single-dish observations were not capable of resolving the chemical differences within the regions, interferometric studies toward a few sources have revealed the spatial complexity of the chemistry in HMCs (e.g., *Blake et al.*, 1996; *Wyrowski et al.*, 1999; *Beuther et al.*, 2005a). Here, we present studies toward W3(H<sub>2</sub>O)/OH and Orion-KL as prominent chemical show-cases.

**W3(H<sub>2</sub>O):** The Hot Core region W3(H<sub>2</sub>O)  $6''$  east of the UCHII region W3(OH) exhibits an H<sub>2</sub>O maser outflow and a synchrotron jet (*Alcolea et al.*, 1993; *Wilner et al.*, 1999). Follow-up observations with the Plateau de Bure Interferometer (PdBI) reveal dust emission associated with the synchrotron jet source and a large diversity of molecular line emission between the UCHII region W3(OH) and the Hot Core W3(H<sub>2</sub>O) (*Wyrowski et al.*, 1997, 1999). Nitrogen-bearing molecules are observed only

toward W3(H<sub>2</sub>O), whereas oxygen-bearing species are detected from both regions. Based on HNC/O observations, Wyrowski *et al.* (1999) estimate gas temperatures toward W3(H<sub>2</sub>O) of  $\sim 200$  K, clearly confirming the hot core nature of the source. The differences in oxygen- and nitrogen-bearing species are manifestations of chemical evolution due to different ages of the sources.

*Orion-KL*: One of the early targets of the recently completed Submillimeter Array (SMA) was the prototypical HMC Orion-KL. *Beuther et al.* (2004, 2005a, 2006) observed the region in the  $865\ \mu\text{m}$  and  $440\ \mu\text{m}$  windows and resolved the submm continuum and molecular line emission at  $1''$  resolution. The continuum maps resolved the enigmatic source *1* from the hot molecular core, detected source *n* for the first time shortward of 7 mm and furthermore isolated a new protostellar source SMA1, emitting strong line emission. The observed 4 GHz bandpass in the  $865\ \mu\text{m}$  band revealed more than 145 lines from various molecular species with considerable spatial structure. Fig. 2 shows an SMA example spectrum and representative line images. SiO emission is observed from the collimated north-east south-west outflow and the more extended north-west south-east outflow. Typical hot core molecules like  $\text{CH}_3\text{CN}$  and  $\text{CH}_3\text{CH}_2\text{CN}$  follow the hot core morphology known from other molecules and lower frequency observations (e.g., *Wright et al.*, 1996; *Blake et al.*, 1996; *Wilson et al.*, 2000). In contrast to this, oxygen-bearing molecules like  $\text{CH}_3\text{OH}$  or  $\text{HCOOCH}_3$  are weaker toward the hot molecular core, but they show strong emission features a few arcseconds to the south-west, associated with the so-called compact ridge. Many molecules, in particular sulphur-bearing species like  $\text{C}^{34}\text{S}$  or  $\text{SO}_2$ , show additional emission further to the north-east, associated with IrC6.

Although existing chemical models predict the evolution and production paths of various molecules (e.g., *Charnley, 1997; van Dishoeck and Blake, 1998; Doty et al., 2002; Nomura and Millar, 2004; Viti et al., 2004*), we are certainly not at the stage where they can reliably predict the chemical structure of HMCs. Considering the complexity of the closest region of massive star formation, Orion-KL, it is essential to get a deeper understanding of the basic chemical and physical processes, because otherwise the confidence in studies of regions at larger distances is greatly diminished. On the positive side, a better knowledge of the chemical details may allow us to use molecular line observations as chemical clocks for (massive) star-forming regions.

### 3.2. Theory

The critical difference between low- and high-mass star formation is that low-mass stars form in a time  $t_{*f}$  short compared to the Kelvin-Helmholtz time  $t_{\text{KH}}$ , whereas high-mass stars generally have  $t_{\text{KH}} \lesssim t_{*f}$  (Kahn 1974). As a result, low-mass stars undergo extensive pre-main sequence evolution after accretion has finished, whereas the highest mass stars can accrete a significant amount of mass while on the main sequence. The feedback associated with the in-

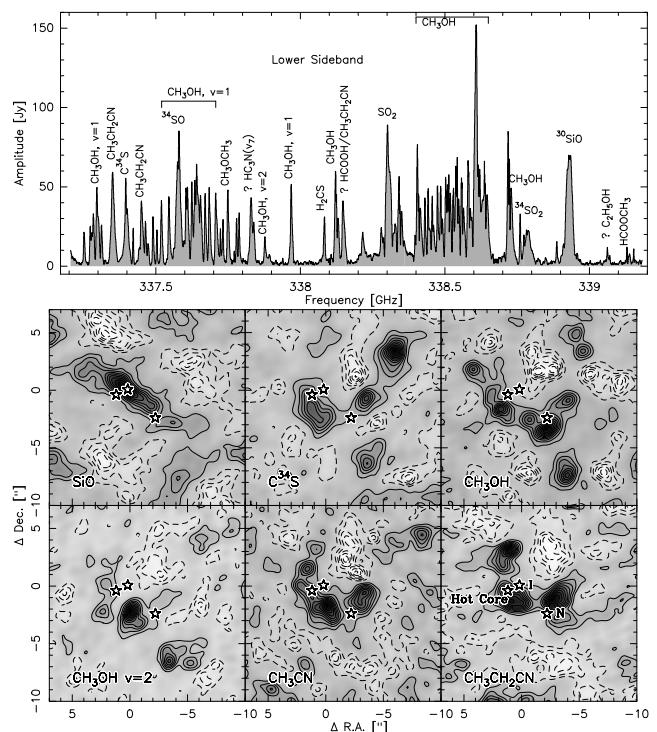


Fig. 2.— Submillimeter Array spectral line observations in the  $850\,\mu\text{m}$  band toward Orion-KL from *Beuther et al.* (2005a). The top panel shows a vector-averaged spectrum in the uv-domain on a baseline of 21 m. The bottom panel presents representative images from various molecular species. Full contours show positive emission, dashed contours negative features due to missing short spacings and thus inadequate cleaning. The stars mark the locations of source *I*, the Hot Core peak position and source *n* (see bottom-right panel).

tense radiation produced by high-mass stars will be considered in §4; here we ask whether high-mass star formation differs significantly from low-mass star formation. At the time of the last Protostars and Planets conference, *Stahler et al.* (2000) argued that it does.

The conventional view remains that high-mass star formation is a scaled up version of low-mass star formation, with an accretion rate  $\dot{m}_* \simeq c^3/G$ , where the effective sound speed  $c$  includes the effects of thermal gas pressure, magnetic pressure, and turbulence (*Stahler et al.*, 1980). *Wolfire and Cassinelli* (1987) found that accretion rates of order  $10^{-3} M_\odot \text{ yr}^{-1}$  are needed to overcome the effects of radiation pressure, and attributed this to the high values of  $c$  in high-mass star forming regions. By modeling the SEDs of high-mass protostars, *Osorio et al.* (1999) inferred that high-mass stars form in somewhat less than  $10^5$  yr. They favored a logatropic model, in which the ambient density varies as  $r^{-1}$  away from the protostar. *McKee and Tan* (2002, 2003) critiqued logatropic models and developed the Turbulent Core Model, in which massive stars

form from gravitationally bound cores supported by turbulence and magnetic fields. They argued that on scales large compared to the thermal Jeans mass, the density and pressure distributions in turbulent, gravitationally bound cores and clumps should be scale free and vary as powers of the radius (e.g.,  $\rho \propto r^{-k_\rho}$ ). As a result, the core and the star-forming clump in which it is embedded are polytropes, with  $P \propto \rho^{\gamma_p}$ . The gravitational collapse of a polytrope that is initially in approximate equilibrium results in an accretion rate  $\dot{m}_* \propto m_*^q$ , with  $q = 3(1 - \gamma_p)/(4 - 3\gamma_p)$  (McLaughlin and Pudritz, 1997). Isothermal cores have  $q = 0$ , whereas logatropes ( $\gamma_p \rightarrow 0$ ) have  $q = \frac{3}{4}$ . (It should be noted that the numerical simulations of Yorke and Sonnhalter, 2002, generally have  $q < 0$  due to feedback effects. This simulation differs from the turbulent core model in that the initial conditions were non-turbulent and the restriction to two dimensions overemphasizes feedback effects—§4.2.) Regions of high-mass star formation have surface densities  $\Sigma \sim 1 \text{ g cm}^{-2}$  (Plume et al., 1997), corresponding to visual extinctions  $A_V \sim 200 \text{ mag}$ . McKee and Tan (2003) showed that the typical accretion rate and the corresponding time to form a star of mass  $m_{*f}$  in such regions are

$$\dot{m}_* \simeq 0.5 \times 10^{-3} \left( \frac{m_{*f}}{30 M_\odot} \right)^{3/4} \Sigma_{\text{cl}}^{3/4} \left( \frac{m_*}{m_{*f}} \right)^{0.5} \frac{M_\odot}{\text{yr}},$$

$$t_{*f} \simeq 1.3 \times 10^5 \left( \frac{m_{*f}}{30 M_\odot} \right)^{1/4} \Sigma_{\text{cl}}^{-3/4} \text{ yr},$$

where  $\Sigma_{\text{cl}}$  is the surface density of the several thousand  $M_\odot$  clump in which the star is forming and where they adopted  $k_\rho = \frac{3}{2}$  as a typical value for the density power law in a core. The radius of the core out of which the star forms is  $0.06(m_{*f}/30 M_\odot)^{1/2} \Sigma_{\text{cl}}^{1/2} \text{ pc}$ . Observed star clusters in the Galaxy have surface densities comparable to those of high-mass star forming regions, with values ranging from about  $0.2 \text{ g cm}^{-2}$  in the Orion Nebula Cluster to about  $4 \text{ g cm}^{-2}$  in the Arches Cluster (McKee and Tan, 2003). This work has been criticized on two grounds: First, it approximates the large-scale macro-turbulence in the cores and clumps as a local pressure (micro-turbulence), which is equivalent to ignoring the surface terms in the virial equation (e.g., Mac Low 2004). This approximation is valid provided the cores and clumps live for a number of free-fall times, so that they are in quasi-equilibrium. Evidence that clumps are quasi-equilibrium structures will be discussed in §5.2; being smaller, cores are likely to experience greater fluctuations, so the quasi-equilibrium approximation is probably less accurate for them. Second, the turbulent core model assumes that most of the mass in the core that is not ejected by outflows will go into a single massive star (or binary). Dobbs et al. (2005) investigated this assumption by simulating the collapse of a high-mass core similar to that considered by McKee and Tan (2003). In the isothermal case, Dobbs et al. found that the core fragmented into many pieces, which is inconsistent with the formation of a massive star. With a more realistic equation of state, however, only a few fragments formed, and when the heating due

to the central protostar is included, even less fragmentation occurs (Krumholz et al. 2005b). Furthermore, the level of turbulence in the simulations by Dobbs et al. (2005) is significantly less than the observed value.

Variants of the gravitational collapse model in which the accretion rate accelerates very rapidly have also been considered ( $\dot{m}_* \propto m_*^q$  with  $q > 1$ , so that  $m_* \rightarrow \infty$  in a finite time in the absence of other effects). However, such models have accretion rates that can exceed the value  $\dot{m}_* \propto c^3$  that is expected on dynamical grounds. Behrend and Maeder (2001) assumed that the accretion rate onto a protostar is proportional to the observed mass loss rate in the protostellar outflow and found that a massive star could form in  $\sim 3 \times 10^5 \text{ yr}$ . This phenomenological model has  $q \simeq 1.5$ , the value adopted in an earlier model by Norberg and Maeder (2000). However, it is not at all clear that the accretion rate onto the protostar is in fact proportional to the observed mass outflow rates. Keto (2002, 2003) modeled the growth of massive stars as being due to Bondi accretion, so that the accretion rate is  $\dot{m}_* \propto m_*^2$ , under his assumption that the ambient medium has a constant density and temperature. As Keto points out, the Bondi accretion model assumes that the self-gravity of the gas is negligible. The condition that the mass within the Bondi radius  $Gm_*/c^2$  be much less than the stellar mass can be shown to be equivalent to requiring  $\dot{m}_* \lesssim c^3/G$ ; for the value of  $c \simeq 0.5 \text{ km s}^{-1}$  considered by Keto, this restricts the accretion rate to  $\dot{m}_* \lesssim 3 \times 10^{-5} M_\odot \text{ yr}^{-1}$ , smaller than the values he considers. (One can show that when one generalizes the Bondi accretion model to approximately include the self gravity of the gas, the accretion rate is indeed about  $c^3/G$  if the gas is initially in virial equilibrium.) Schmeja and Klessen (2004) analyze mass accretion rates in the framework of gravo-turbulent fragmentation, and they find that the accretion rates are highly time-variant, with a sharp peak shortly after the formation of the protostellar core. Furthermore, in their models the peak and mean accretion rates increase with increasing mass of the final star.

Most models for (proto)stellar structure and evolution do not yet include the effects of rotation (e.g., Meynet and Maeder 2005), which are expected to be relatively large given the recent accumulation of stellar material from the accretion disk. In models of gravo-turbulent fragmentation, Jappsen and Klessen (2004) find that the angular momentum  $j$  correlates with the core mass  $M$  like  $j \propto M^{2/3}$ . Furthermore, they conclude that the angular momentum evolution is approximately consistent with the contraction of initially uniform density spheres undergoing solid body rotation. The precise amount of stellar angular momentum depends on how the accretion and outflow from the star-disk interaction region is modulated by magnetic fields and on the strength of the stellar wind (e.g., Matt and Pudritz, 2005). One potentially important effect is the variation in photospheric temperature from the equatorial to polar regions, which can enhance the beaming of bolometric and ionizing luminosity along the polar directions.

Alternative models for high-mass star formation have

been developed by *Bonnell* and collaborators (e.g., *Bonnell et al.*, 1998, 2004). In the competitive accretion model, small stars ( $m_* \sim 0.1 M_\odot$ ) form via gravitational collapse, but then grow by gravitational accretion of gas that was initially unbound to the star – i.e., by Bondi-Hoyle accretion, with allowance for the possibility that tidal effects can reduce the accretion radius (*Bonnell et al.*, 2001a, 2004). This model naturally results in segregating high-mass stars toward the center of the cluster, as observed. Furthermore, it gives a two-power law IMF that is qualitatively consistent with observation (*Bonnell et al.* 2001b). Simulations by *Bonnell et al.* (2004) are consistent with this model. However, there are two significant difficulties: First, radiation pressure disrupts Bondi-Hoyle accretion once the stellar mass exceeds  $\sim 10 M_\odot$  (*Edgar and Clarke*, 2004), so it is unlikely that competitive accretion can operate at masses above this. There is no evidence for a change in the IMF in this mass range, however, which suggests that competitive accretion does not determine the IMF at lower masses either. Second, competitive accretion is effective only if the virial parameter is much less than observed: Based on simulations of Bondi-Hoyle accretion in a turbulent medium, *Krumholz et al.* (2005c, 2006) show that protostars of mass  $m_* \sim 0.1 M_\odot$  can accrete more than their initial mass in a dynamical time only if  $\alpha_{\text{vir}} \lesssim 0.1 (10^3 M_\odot / M_{\text{cl}})^{1/2}$ . Such low values of  $\alpha_{\text{vir}}$  do appear in the simulations, but, as discussed above, not in observed high-mass star-forming regions, which have masses  $M_{\text{cl}}$  of hundreds to thousands of solar masses. Since the expected amount of mass accreted in a dynamical time is small, *Krumholz et al.* conclude that stars form via gravitational collapse of individual cores (Fig. 3). *Bonnell et al.* (this volume) argue that both difficulties can be ameliorated if the clump in which the massive stars are forming is undergoing global gravitational collapse. *Tan et al.* (in prep.) present arguments against such dynamical collapse in the formation of star clusters. It is thus very important to observationally determine the nature of the motions in massive star-forming clumps: are they dominated by turbulence or by collapse?

The most radical and imaginative model for the formation of high-mass stars is that they form via stellar collisions during a brief epoch in which the stellar density reaches  $\sim 10^8$  stars  $\text{pc}^{-3}$  (e.g., *Bonnell et al.*, 1998; *Bonnell and Bate*, 2002), far greater than observed in any Galactic star cluster (the densest region reported so far is W3 IRS5 with an approximate stellar density of  $10^6$  stars  $\text{pc}^{-3}$ , *Megeath et al.*, 2005). This model also results in an IMF that is in qualitative agreement with observation, although it must be borne in mind that the simulations to date have not included feedback. In their review, *Stahler et al.* (2000) supported the merger model, emphasizing that gas associated with protostars could increase the effective collision cross section and permit merging to occur at lower stellar densities. More recently, *Bonnell and Bate* (2005) have suggested that binaries in clusters will evolve to smaller separations due to accretion, resulting in mergers. However, a key assumption in this model is that there is no net angular momen-

tum in the accreted gas, which makes sense in the competitive accretion model but not the gravitational collapse model. Stellar dynamical calculations by *Portegies Zwart et al.* (2004), which did not include any gas, show that at densities  $\gtrsim 10^8$  stars  $\text{pc}^{-3}$  it is possible to have runaway stellar mergers at the center of a star cluster, which they suggest results in the formation of an intermediate mass black hole. It should be noted that they inferred that this could have occurred based on the currently observed properties of the star cluster (although with the assumption that the tidal radius is greater than 100 times the core radius), not on a hypothetical ultra-dense state of the cluster. *Bally and Zinnecker* (2005) discuss observational approaches to testing the merger scenario, and suggest that the wide-angle outflow from OMC-1 in the Orion molecular cloud could be due to a protostellar merger that released  $10^{48} - 10^{49}$  erg. While it is quite possible that some stellar mergers occur near the centers of some star clusters, the hypothesis that stellar mergers are responsible for a significant fraction of high-mass stars faces several major hurdles: (1) the hypothesized ultra-dense state would be quite luminous due to the massive stars, yet has never been observed; (2) the mass loss hypothesized to be responsible for reducing the cluster density from  $\sim 10^8$  stars  $\text{pc}^{-3}$  to observed values must be finely tuned in order to decrease the magnitude of the binding energy by a large factor; and (3) it is difficult to see how this model could account for the observations of disks and collimated outflows discussed in §3.1 and 4.1.

## 4. Feedback processes in massive star formation

### 4.1. Observational results

Hypercompact HII regions: Hypercompact HII regions (HCHII) are smaller, denser, and brighter than UCHII regions. Specifically, they are defined as having diameters less than 0.01 pc, consistent with being small photoionized nebulae produced by O or B stars. None have more ionizing flux than can be provided by a single O or B star. Their common properties that distinguish them from UCHII regions are:

- 1) They are  $\gtrsim 10$  times smaller ( $\leq 0.01$  pc) and  $\sim 100$  times denser than UCHII regions with emission measures  $\geq 10^8$  pc  $\text{cm}^{-6}$  (*Kurtz*, 2002, 2005).
- 2) They have rising radio spectral indices  $\alpha$  (where  $S_\nu \propto \nu^\alpha$ ) from short cm to mm wavelengths, and  $\alpha$  ranges from  $\sim 0.3$  to  $1.6$  with a typical value of  $\sim 1$  (e.g., *Churchwell*, 2002; *Hofner et al.*, 1996). They are very faint or not detected at wavelengths longward of 1 cm. The power-law spectra span too large a range in frequency to be the transition from optically thick to thin emission in a constant density nebula.
- 3) In massive star formation regions, they often appear in tight groups of two or more components (*Sewilo et al.*, 2004), reminiscent of the Trapezium in Orion.
- 4) Many but not all HCHII regions have unusually broad radio recombination lines (RRLs;  $\text{FWHM} \geq 40 \text{ km s}^{-1}$ ). Some have  $\text{FWHMs} > 100 \text{ km s}^{-1}$  (*Sewilo et al.*, 2004).



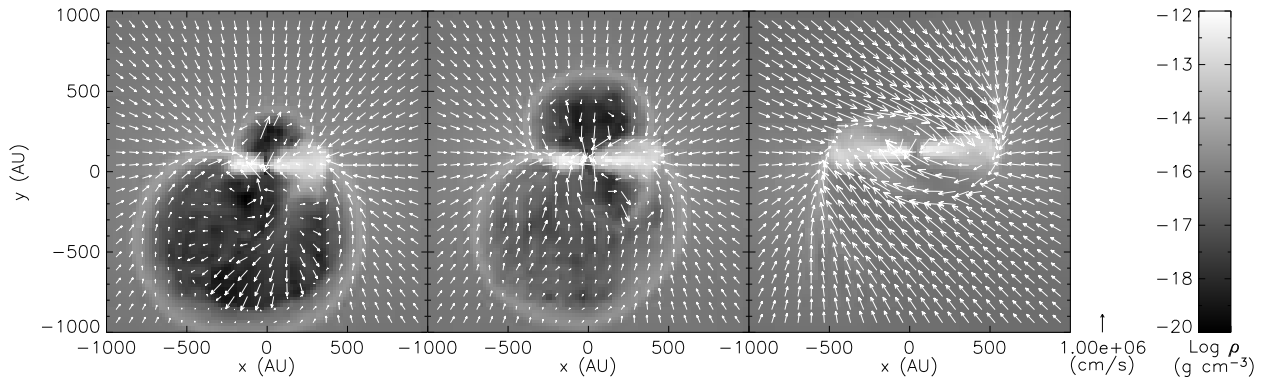


Fig. 3.— This plot from *Krumholz et al.* (2005b) shows 3D radiation hydrodynamic simulations of the collapse of a massive core. It is a slice in the XY plane at three different times showing the initial growth, instability and collapse of a radiation bubble. The times of the three slices are  $1.5 \times 10^4$ ,  $1.65 \times 10^4$ , and  $2.0 \times 10^4$  years, and the (proto)stellar masses are 21.3, 22.4 and 25.7  $M_{\odot}$ . The density is shown in gray-scale and the velocity as arrows.

5) They are often (always?) coincident with strong water masers (e.g., *Hofner and Churchwell*, 1996; *Carral et al.*, 1997) and possibly other masers also, but the latter has not yet been observationally established.

What is the nature of HCHII regions? Their compactness, multiplicity, range of luminosities, and coincidence with water masers all argue for ionization by a single or possibly a binary system of late O or B star(s) at an age younger than UCHII regions. Their broad RRLs indicate highly dynamic internal structures (outflow jets, disk rotation, expansion, shocks, accretion, etc.) the nature of which is not yet understood. The fact that only about half of the HCHIIIs that have observed RRLs have broad lines would argue that this phase is short-lived, perhaps only apparent in the first half of an HCHII region's lifetime, provided the accretion rate is larger during the early stages of the HCHIIIs. Their radio spectral indices have implications for the internal density structure, but here also too little observational information is available to do more than speculate at this juncture. The power-law spectra can be produced by a clumpy nebula (*Ignace and Churchwell*, 2004), but this is only one of several possibilities that needs to be investigated (e.g., *Keto*, 2003; *Tan and McKee*, 2003). It is not clear yet whether they form after the HMC stage or whether HMCs and HCHIIIs coexist.

**Outflows:** Massive molecular outflows are among the most studied phenomena in massive star formation over the last decade, and the observations range from statistical studies of large samples at low spatial resolution to individual case studies at high spatial resolution. Because (massive) molecular outflows are presented in the chapter by *Arce et al.*, here we only discuss their general properties and implications for the massive star-forming processes.

Since the early statistical work by *Shepherd and Churchwell* (1996) it is known that massive molecular outflows are an ubiquitous phenomenon in massive star formation. Early observations indicated that massive outflows appear less collimated than their low-mass counterparts, imply-

ing potentially different formation scenarios for the outflows and the massive star-forming processes (e.g., *Richer et al.*, 2000; *Shepherd et al.*, 2003). However, *Beuther et al.* (2002b) showed that outflows from HMPOs, even if observed only with single-dish instruments, are consistent with collimated outflows if one considers the large distances, projection effects and poor angular resolution carefully (see also *Kim and Kurtz*, 2006). Interferometric follow-up studies revealed more massive star-forming regions with molecular outflows consistent with the collimated outflows known from low-mass star formation (for a compilation see *Beuther and Shepherd*, 2005). Since collimated structures are hard to maintain over a few  $\times 10^4$  years (the typical dynamical timescales of molecular outflows) if they are associated with colliding protostars within the cluster centers, these outflow observations strongly support the accretion-based formation scenario in massive star formation.

We note that no highly collimated outflow has been observed for high-mass star-forming regions exceeding  $10^5 L_{\odot}$ , corresponding to approximately 30  $M_{\odot}$  stars. Therefore, these data cannot exclude that stars more massive than that may form via different processes. However, there are other possibilities to explain the current non-observations of collimated outflows at the high-luminosity end. An easy explanation would be that these sources are so exceptionally rare that we simply have not been lucky enough to detect one. Alternatively, *Beuther and Shepherd* (2005) recently suggested an evolutionary sequence that explains qualitatively the present state of observational facts (see also the chapter by *Arce et al.*): To form massive early O-stars via accretion, the protostellar objects have to go through lower-mass stages as well. During the early B-star stage, the accreting protostars can drive collimated outflows as observed. Growing further in mass and luminosity, they develop HCHII regions in the late O-star stage, and collimated jets and less collimated winds can coexist,

producing bipolar outflows with a lower degree of collimation. In this scenario, it would be intrinsically impossible to ever observe jet-like outflows from young early O-type protostars. Alternatively, the effect may be due to greater observational confusion of the outflows from very luminous sources with those from surrounding lower-mass protostars, since the more luminous sources tend to be in richer, more distant clusters. These evolutionary models for massive molecular outflows have to be tested further against theory and observations.

## 4.2. Theory

Feedback processes that act against gravitational collapse and accretion of gas to protostars include radiation pressure (transmitted via dust grains, and, for sufficiently massive stars, by electron scattering), thermal pressure of photo-ionized gas, ram pressure from protostellar winds, and main sequence stellar winds. These processes become increasingly important with protostellar mass and may reduce the efficiency of star formation from a given core. There is good evidence for a cutoff in the stellar IMF at around  $150 M_{\odot}$  (e.g., *Weidner and Kroupa*, 2004; *Figer*, 2005), but it remains to be determined whether this is due to feedback processes or to instabilities in massive stars.

For individual low-mass star formation from a core, bipolar protostellar outflows, accelerated from the inner accretion disk and star by rotating magnetic fields, appear to be the dominant feedback mechanism, probably preventing accretion from polar directions and also ejecting a fraction, up to a third, of the material accreting through the disk. This leads to star formation efficiencies from the core of order 30-50% (*Matzner and McKee*, 2000).

For massive protostars, forming in the same way from a core and accretion disk, one expects similar MHD-driven outflows to be present, leading to similar formation efficiencies. In addition, once the massive protostar has contracted to the main sequence (this can occur rapidly before accretion has finished), it starts to produce a large flux of ionizing photons. The resulting HCHII region is likely to be confined in all but the polar directions by the protostellar jets (*Tan and McKee*, 2003). This could provide an important potential observational diagnostic for the physics of protostellar jets, as they might be illuminated along the axis by the ionizing radiation. As the protostellar mass and ionizing flux increase, the HCHII region can eventually burn its way through the jet and begin to ionize the disk surface. If the disk is ionized out to a radius where the escape speed is about equal to the ionized gas sound speed, then a photo-evaporated flow is set up, reducing accretion to the star (*Hollenbach et al.*, 1994).

Observations indicate that outflows may be less well collimated for luminosities above about  $10^5 L_{\odot}$  (§4.1). As discussed above, *Beuther and Shepherd* (2005) have suggested that this is due to a decrease in the collimation of the protostellar jet with increasing protostellar luminosity. A possible mechanism for this is suggested by the work of *Fendt*

and *Cameljic* (2002), who simulated protostellar jets with a large turbulent diffusivity and found that the collimation decreases as the diffusivity increases. Applying this picture to massive outflows, the level of turbulence in the accretion flow would have to grow as the luminosity of the protostar increases.

The importance of massive molecular outflows in driving turbulence in molecular clouds is not generally agreed upon. *MacLow and Klessen* (2004, and references therein) argue that although molecular outflows are very energetic, they deposit most of their energy at low densities. Furthermore, since the molecular gas motions show increasing power all the way up to the largest cloud complexes, *MacLow and Klessen* (2004) conclude that it would be hard to fathom how such large scales should be driven by embedded protostars. Contrary to this, on the relatively small scales of the clumps, if the energy of turbulent motions decays with a half-life of one dynamical time, then protostellar outflows from star formation are able to maintain turbulence if 50% of the gas mass forms stars in 20 dynamical times, and 1% of the resulting outflow energy couples to the ambient gas (*Tan*, 2006). Recently, *Quillen et al.* (2005) reported that their observations toward the low-mass star-forming region NGC1333 are also consistent with outflow driven turbulence, and, as remarked in §2.2, *Li and Nakamura* (in prep.) have given theoretical support to this idea. It becomes more difficult for this mechanism to support turbulence on larger scales in the GMC involving greater gas masses; on these scales, *Matzner* (2002) has shown that energy injection by HII regions dominates that by protostellar outflows and can support the observed level of turbulence. Alternatives to protostellar driving of the turbulence in molecular clouds are discussed in §2.2.

Radiation pressure on dust grains (well-coupled to the gas at these densities) is also important for massive protostars. It has been suggested, in the context of spherical accretion models, that this leads to an upper limit to the initial mass function (*Kahn*, 1974; *Wolfire and Cassinelli*, 1987). The difficulties faced by spherical accretion models was a major motivation for the formation model via stellar collisions (*Bonnell et al.*, 1998). However, massive star formation becomes easier once a disk geometry is allowed for (e.g., *Nakano*, 1989; *Jijina and Adams*, 1996). *Yorke and Sonnhalter* (2002) used 2D axially symmetric simulations to follow massive star formation from a core collapsing to a disk, including radiation pressure feedback; accretion stopped at  $43 M_{\odot}$  in their most massive core. They showed the accretion geometry channeled radiative flux into the polar directions and away from the disk, terming this the “flashlight effect”. *Krumholz et al.* (2005a) found that cavities created by protostellar outflows increase the flashlight effect, allowing even higher final masses. The first 3D simulation of massive star formation shows that instabilities facilitate the escape of radiation and allow the formation of stars significantly more massive than suggested by 2D calculations (Fig. 3, *Krumholz et al.*, 2005b).

The high accretion rates required to form massive stars

tend to quench HCHII regions (Walmsley, 1995). For spherical accretion, the density profile in a freely infalling envelope is  $\rho \propto r^{-3/2}$ . As a result, the radius of the HCHII region is

$$R_{\text{HCHII}} = R_* \exp(S/S_{\text{cr}}),$$

where  $S$  is the ionizing photon luminosity and

$$S_{\text{cr}} = \frac{\alpha^{(2)} \dot{m}_*^2}{8\pi \mu_{\text{H}}^2 G m_*} = 5.6 \times 10^{50} \left( \frac{\dot{m}_{*, -3}^2}{m_{*, 2}} \right) \text{ s}^{-1}$$

(Omukai and Inutsuka, 2002). Here  $\alpha^{(2)}$  is the recombination coefficient to excited states of hydrogen,  $\dot{m}_{*, -3} = \dot{m}_*/(10^{-3} M_{\odot} \text{ yr}^{-1})$  and  $m_{*, 2} = m_*/(100 M_{\odot})$ ; we have replaced  $m_p$  in their expression with  $\mu_{\text{H}} = 2.34 \times 10^{-24}$  g, the mass per hydrogen nucleus. When the radius of the HCHII region is small enough that the infall velocity exceeds the velocity of an R-critical ionization front ( $2c_i$ , where  $c_i \simeq 10 \text{ km s}^{-1}$  is the isothermal sound speed of the ionized gas), the HCHII region is said to be "trapped" (Keto, 2002): There is no shock in the accretion flow and the HCHII region cannot undergo the classical pressure-driven expansion. The ionizing photon luminosity  $S$  increases rapidly with  $m_*$ . If the accretion rate depends on stellar mass such that the critical luminosity  $S_{\text{cr}}$  is approximately independent of mass (e.g., the standard McKee and Tan (2003) model has  $\dot{m}_* \propto m_*^{1/2}$ , so that  $S_{\text{cr}} = \text{const.}$ ), then the radius of the HCHII region expands as  $\exp(S)$  and the trapped phase is relatively brief. On the other hand, if  $S_{\text{cr}}$  increases rapidly with mass, as in the Bondi accretion model ( $\dot{m}_* \propto m_*^2$ ), then the expansion is retarded, leading to the possibility that the trapped phase of the HCHII region could last for much of the life of the protostar (Keto, 2003). However, as outlined in §3.2, the parameters adopted by Keto (2003) are not consistent with the neglect of the self-gravity of the gas.

The evolution of the HCHII region changes substantially due to rotation of the infalling gas. The density is significantly lower above the accretion disk (Ulrich, 1976), so trapped HCHII regions will generally expand out to the radius of the accretion disk; when this is larger than the gravitational radius  $R_g = Gm_*/c_i^2$ , then the HCHII region is no longer trapped (McKee and Tan, in prep.). Keto and Wood (2006) have also considered the effects of disks in massive protostars: They point out that it is possible to form an ionized accretion disk, and suggest that there is evidence for this in G10.6-04.

## 5. Formation of star clusters with massive stars

### 5.1. Observational results

**IMF:** The formation of the Initial Mass Function (IMF) has been an important issue in star formation research since the early work by Salpeter (1955). For a current summary of IMF studies see Corbelli et al. (2005) and references therein, and the chapter by Bonnell et al.. One of the questions in the context of this review is whether the

IMF is determined already at the earliest stages of cluster formation by the initial gravo-turbulent fragmentation processes of molecular clouds (e.g., Padoan and Nordlund, 2002; MacLow and Klessen, 2004), or whether the IMF is determined by subsequent processes like competitive accretion or feedback processes from the underlying star-forming cluster (e.g., Bonnell et al., 2004; Ballesteros-Paredes et al., 2006). (Sub)mm continuum studies of young low-mass clusters have convincingly shown that the core mass function at the beginning of low-mass cluster formation already resembles the stellar IMF (Motte et al., 1998; Johnstone et al., 2001; Enoch et al., 2006; and the chapter by Lada et al.). Because massive star-forming regions are on average more distant, resolving these clusters is difficult. However, several single-dish studies of different high-mass star-forming regions at early evolutionary stages have shown that at high clump masses, the cumulative mass distributions are consistent with the slope of the high-mass stellar IMF (Shirley et al., 2003; Williams et al., 2004; Reid and Wilson, 2005; Beltrán et al., 2006). Furthermore, the only existing high-spatial-resolution interferometric study that resolves a massive star-forming clump into a statistically meaningful number of cores also finds the core mass distribution to be consistent with the stellar IMF (Beuther and Schilke, 2004). Although mm continuum observations alone are ambiguous whether the observed cores and clumps are bound or transient structures, the consistently steeper mass functions observed in mm continuum emission compared with the lower density tracing CO line studies (e.g., Kramer et al., 1998) suggest that the mm-continuum sources could be bound whereas the CO sources could be transient. Furthermore, Belloche et al. (2001) report additional observations supporting the interpretation that the study of Motte et al. (1998) sampled bound sources. Combining these results from massive star formation studies with the previous investigations in the low-mass regime, the apparent similarity between the (cumulative) clump and core mass functions and the stellar IMF supports the idea that the IMF is determined by molecular cloud structure before star formation is initiated, maybe implicating gravo-turbulent fragmentation. However, on a cautionary note, one has to keep in mind that the cumulative mass distributions from single-dish studies as reported above trace scales of cluster formation and thus probably refer to cluster-mass distributions rather than to the IMF. The only way to assess the relationship between the fragmentation of initial high-mass star-forming clumps and the resulting IMF is to carry out high-spatial-resolution interferometric (sub)mm line and continuum studies of a statistically significant sample of (very) young massive star-forming regions.

**First GLIMPSE results:** The GLIMPSE survey is providing an entirely new view of the inner Galaxy with a higher resolution and sensitivity than ever achieved at mid-infrared wavelengths (Benjamin et al., 2003). This is enabling a host of new research on massive star formation as well as many other fields of astronomy. Unfortunately, UCHII regions are generally saturated and too bright in the

IRAC bands to identify the ionizing star(s) and associated clusters above the glaring diffuse PAH emission found toward all these objects. The known HCHII regions are also bright in the GLIMPSE survey. Bipolar outflows stand out in the  $4.5\ \mu\text{m}$  band, providing a powerful way to identify many new outflows in the inner Galaxy. Numerous outflows have been identified in the survey and a catalog of them is being assembled by the GLIMPSE team. The mechanism responsible for this emission is believed to be line emission from shocked  $\text{H}_2$  and/or CO bands; the shocks are produced by outflowing gas ramming into the ambient interstellar medium. Near-infrared spectroscopic observations of molecular  $\text{H}_2$  or CO between  $4.1$  and  $4.7\ \mu\text{m}$  are needed to determine which interpretation is correct.

Within  $\sim 45^\circ$  of the Galactic Center, hundreds of IRDCs are apparent in silhouette against the diffuse infrared background (Fig.1). A catalog of many IRDCs is being prepared for publication by the GLIMPSE team. These clouds are optically thick at  $8\ \mu\text{m}$ , implying visual extinctions  $\geq 50\ \text{mag}$  (see §2.1). The GLIMPSE images are striking in part because of the large number of bubbles contained in them; there are about 1.5 bubbles per square degree on average. A catalog of 329 bubbles has been identified and a web accessible image archive will accompany the archive (Churchwell *et al.*, in prep.). It is found that the bubbles are associated with HII regions and stellar clusters. Only three are associated with supernova remnants and none with planetary nebulae or Wolf Rayet stars. About 1/3 of the bubbles appear to be produced by the stellar winds and radiation pressure from O and B stars (i.e., massive star-forming regions). About 2/3 of the bubbles have small angular diameters (typically only 3-4 arcmin) and do not coincide with a radio HII region or known cluster; these are believed to be driven by B4-B9 stars that have strong enough winds to form a resolved bubble and have enough UV radiation to excite PAH features, but not enough UV photons to ionize a detectable HII region.

One of the most exciting prospects from the GLIMPSE survey is the possibility of identifying the entire population of HMPOs and lower mass protostars from the approximately 50 million stars in the GLIMPSE archive. This is now possible with the large archive of radiative transfer models of protostars calculated for the entire range of protostellar masses, the full range of suspected accretion rates, disk masses, and orientations of the accretion disks to the line of sight (Whitney *et al.*, in prep.). Model photospheres for main sequence stars and red giants are included in the model archive as well, so it is possible to distinguish reddened main sequence stars and red giants from protostars and slightly evolved young stellar objects. What makes this archive of models powerful, however, is the model fitter that will fit the best models to observed SEDs of large numbers of sources, giving: the mass, spectral types, approximate evolutionary state, and interstellar extinction for the best fit models to every source (Robitaille *et al.*, in prep.). This will provide a powerful alternative to the classical method of estimating the global star formation rate in the Galaxy

based on measured UV photon luminosities of radio HII regions and an assumed initial mass function.

## 5.2. Theory

In the local universe, massive star and star cluster formation are intrinsically linked: massive stars almost always appear to form in clusters (De Wit *et al.*, 2005). We have seen that this is a natural expectation of models of star formation from cores, since the accretion rates are higher if the core is pressurized by the weight of a large clump of gas. This scenario predicts that massive stars tend to form near the center of the clump and that there can be extensive star formation (mostly of lower-mass stars) from the clump's gas while massive star formation is ongoing.

Presently there is no consensus on whether massive stars form preferentially at the centers of clusters, since, although they are often observed in central locations, it is possible that they could have migrated there by dynamical interactions after their formation. Bonnell and Davies (1998) found that the mass segregation time of clusters with mass-independent initial velocity dispersions was similar to the relaxation time,  $t_{\text{relax}} \simeq 0.1N/(\ln N)t_{\text{dyn}}$  for  $N$  equal mass stars, i.e., about 14 crossing timescales for  $N = 1000$ . The presence of gas should shorten these timescales (Ostriker, 1999). To resolve this issue, we need to measure the cluster formation time: does it take few or many dynamical times? Elmegreen (2000) presented a number of arguments for rapid star formation in  $\sim 1$ -2 dynamical timescales, including scales relevant to star clusters. Tan *et al.* (in prep.) presented arguments for somewhat longer formation timescales and argued that star formation in clusters is a quasi-equilibrium process. For example, the age spread of stars in the Orion Nebula Cluster is at least 2.5 Myr (Palla and Stahler, 1999), while the dynamical time is only  $7 \times 10^5\ \text{yr}$  for the cluster as a whole, and is much shorter in the central region. A relatively long formation timescale is also consistent with the observed morphologies of protoclusters in CS molecular lines: Shirley *et al.* (2003) found approximately spherical and centrally concentrated morphologies for a large fraction of their sources, suggesting they are older than a few dynamical times. Long formation timescales mean that the observed central locations of massive stars could be due either to central formation or mass segregation (or both). A corollary of long formation timescales is that the level of turbulence in the clump must be maintained, possibly by protostellar outflows and HII regions (see §2.2, §4.2). Studies of the spatial distributions of massive stars in more embedded, presumably less dynamically evolved, clusters should help to resolve this issue.

As with spatial segregation, there is also no consensus about whether there is a temporal segregation in massive star formation from the surrounding cluster: do massive stars form early, late or contemporaneously with the other cluster members? Late formation of massive stars was often proposed, since it was expected that once massive stars were present, they would rapidly disrupt the remaining

gas with their feedback. However, *Tan and McKee* (2001) showed that the impact of feedback was much reduced in a medium composed of dense cores, virialized and orbiting supersonically in the clump potential. *Dale et al.* (2005) have carried out the first simulations of photo-ionizing feedback in clusters and have confirmed that feedback is significantly reduced in realistic, inhomogeneous clumps. The observed numbers of UCHII regions (*Kurtz et al.*, 1994) also suggest that massive star ionizing feedback can be confined inside  $\sim 0.1$  pc for at least  $\sim 10^5$  yr. *Hoogerwerf et al.* (2001) have proposed that four O- and B-stars were ejected 2.5 Myr ago from the Orion Nebula Cluster, where massive star formation is still underway. If true, this would indicate that massive star formation occurred in both the early and late stages of cluster formation.

## 6. Conclusions and future prospects

Observational evidence suggests that stars at least up to  $30 M_{\odot}$  form via an accretion based formation scenario. Venturing to higher mass objects is an important observational future task. Theoretically, stars of all masses are capable of forming via accretion processes but it remains an open question whether Nature follows that path or whether other processes become more important for the highest-mass stars. Recent work suggests that the accretion-based formation scenario in turbulent molecular cloud cores is the more likely way to build most stars of all masses.

Regarding the evolutionary sequence outlined in the Introduction, the HMPO and Final-Star stages have been studied extensively in the past, whereas the earliest stages of massive star formation, i.e., High-Mass Starless Cores and High-Mass Cores harboring Low/Intermediate-Mass Protostars, are just beginning to be explored in more detail. The coming years promise important results for the initial conditions of massive star formation and the origin of the IMF.

One of the observational challenges of the coming decade is to identify and study the properties of genuine accretion disks in high-mass star formation (see also the chapter by *Cesaroni et al.*). Are massive accretion disks similar to their low-mass counterparts, or are they massive enough to become self-gravitating entities? Determining the nature of the broad Radio Recombination Lines in HCHII regions requires high spatial resolution and high sensitivity, which both will be provided by the EVLA and ALMA. Ultimately, we need to understand how outflows are collimated and driven. Do they originate from the surface of the disk? What fraction of the matter that becomes unstable and begins falling toward the star/disk actually makes it into the star versus being thrown back out via bipolar outflows? What fraction of the outflow mass is due to gas entrainment and what fraction is due to recycled infalling gas? At what evolutionary stage is the IMF actually determined? Furthermore, astrochemistry is still poorly investigated, but the advent of large correlator bandwidths now allows us to investigate the chemical census in massive star-forming regions regularly in more detail. An important astrochemical

goal is to establish chemical clocks for star-forming clumps and cores.

The observational capabilities available now and coming online within the next few years are exciting. To mention a few: The SPITZER observatory, and especially the SPITZER surveys GLIMPSE and MIPS GAL will provide an unprecedented census of star-forming regions over large parts of the Galactic Plane. The so far poorly explored far-infrared spectrum will be available with the launches of SOFIA and Herschel. The SMA is currently opening the submm spectral window to high spatial resolution observations, and ALMA will revolutionize (sub)mm interferometry and star formation research in many ways. Near- and mid-infrared interferometry is still in its infancy but early results from the VLTI are very promising. In addition, many existing observatories are upgraded to reach new levels of performance (e.g., PdBI, EVLA, CARMA). Combining the advantages of all instruments, massive star formation research is going to experience tremendous progress in the coming years.

Theorists face the same challenges as observers in understanding the formation and evolution of the molecular clouds and clumps that are the sites of massive star formation, the processes by which individual and binary massive stars form, the origin of the IMF, the strong feedback processes associated with massive star formation, and the interactions that occur in stellar clusters. Here the primary progress is likely to come from simulations on increasingly powerful computers. By the time of the next Protostars and Planets meeting, it should be possible to simulate the formation of a cluster of stars in a turbulent, magnetized medium, to assess the merits of existing theoretical models, and to point the way toward a deeper understanding of massive star formation.

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